

3.5 keV Galactic Emission Line as a Signal from the Hidden Sector

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Abstract

An emission line with energy of $E \sim 3.5$ keV has been observed in galaxy clusters by two experiments. The emission line is consistent with the decay of a dark matter particle with a mass of ~ 7 keV. In this work we discuss the possibility that the dark particle responsible for the emission is a real scalar (ρ) which arises naturally in a $U(1)_X$ Stueckelberg extension of MSSM. In the MSSM Stueckelberg extension ρ couples only to other scalars carrying a $U(1)_X$ quantum number. Under the assumption that there exists a vectorlike leptonic generation carrying both $SU(2)_L \times U(1)_Y$ and $U(1)_X$ quantum numbers, we compute the decay of the ρ into two photons via a triangle loop involving scalars. The relic density of the ρ arises via the decay $H^0 \rightarrow h^0 + \rho$ at the loop level involving scalars, and via the annihilation processes of the vectorlike scalars into $\rho + h^0$. It is shown that the galactic data can be explained within a multicomponent dark matter model where the 7 keV dark matter is a subdominant component constituting only $(1-10)\%$ of the matter relic density with the rest being supersymmetric dark matter such as the neutralino. Thus the direct detection experiments remain viable searches for WIMPs. The fact that the dark scalar ρ with no interactions with the standard model particles arises from a Stueckelberg extension of a hidden $U(1)_X$ implies that the 3.5 KeV galactic line emission is a signal from the hidden sector.

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1 Introduction

Two experiments [1, 2] have seen a 3.5 keV gamma line in the sky. A possible explanation is that it is coming from decay of a dark matter particle. The experiment gives

$$\Gamma^{-1}(\rho \rightarrow \gamma\gamma) = (4 \times 10^{27} - 4 \times 10^{28})s . \quad (1)$$

Several works already exist trying to explain the 3.5 keV line such as from decaying dark particle [3] and emission from a dark atom [4, 5]. Here we consider the possibility that the gamma emission arises from the decay of a real field ρ that arises naturally in a $U(1)_X$ extension of the standard model gauge group [6–9] (see also [10–18]). In the $U(1)_X$ Stueckelberg extension of MSSM we assume that all the MSSM particles are neutral under $U(1)_X$ but that there exists extra matter in the form of a vectorlike multiplet which is charged under $U(1)_X$. As mentioned in such an extension there naturally exists a real scalar particle ρ which couples only to complex scalar particles which are charged under $U(1)_X$. In this work we will assume that extra matter consists of vectorlike multiplets which transform under $SU(2)_L \times U(1)_Y$ as doublets and singlets. We assume that ρ has a mass of ~ 7 keV and it decays to two photons via exchange of these charged scalar fields to produce the galactic 3.5 keV gamma line. Regarding relic density, we assume that the primordial relic density is inflated away and the current relic density arises from the decay of Higgs bosons, and also scalar annihilations. There are many processes that can contribute to the relic density. These are: $h^0 \rightarrow \rho + \rho$, $H^0 \rightarrow \rho + \rho$, $H^0 \rightarrow \rho + h^0$, $\tilde{E}_1 \tilde{\bar{E}}_1 \rightarrow \rho + \rho$, $\rho + h^0$ where E_1 is a charged lepton in the vectorlike multiplet etc. It turns out that the final states with $\rho\rho$ are suppressed by m_ρ^4 and are thus negligible. Further, the contribution of the Higgs boson decays dominate the contribution from the annihilation to the relic density. Within the above model it is found possible to fit the galactic data with the 7 keV scalar dark matter being a subdominant component making up as little as 1%-10% of the total dark matter density with the rest being supersymmetric dark matter such as the neutralino or the gravitino.

The outline of the rest of the paper is as follows: In Section 2 we give a brief description of the Stueckelberg extension of MSSM with inclusion of vectorlike multiplets which are charged both under $SU(2)_L \times U(1)_Y$ and under $U(1)_X$. In Section 3 we give an analysis of lifetime of the ρ decaying into two photons via triangle loops involving scalars charged under $U(1)_X$ and also charged under $U(1)_{\text{em}}$. In Section 4 we give an analysis of the relic density of the ρ which is produced via the decay of the Higgs bosons and via annihilation processes. Here we show that the relic density of the ρ arising from Higgs decay is the dominant component and the annihilation processes are subdominant. In Section 5 we give a numerical analysis where we fit the gamma data from the galactic clusters with ρ as a subdominant component of dark matter. Conclusions are given in

Section 6 while further details of the analysis are given in the appendices.

2 The Model

As mentioned in Section 1 we consider an extra vectorlike leptonic generation V consisting of $L, E^c, N^c, L'^c, E', N'$ with $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_X$ quantum numbers as follows

$$L = \begin{pmatrix} N_L \\ E_L \end{pmatrix} (1, 2, -\frac{1}{2}, 1), \quad E_L^c (1, 1, 1, -1), \quad N_L^c (1, 1, 0, -1), \quad (2)$$

$$L'^c = \begin{pmatrix} E_L'^c \\ N_L'^c \end{pmatrix} (1, 2, \frac{1}{2}, -1), \quad E_L' (1, 1, -1, 1), \quad N_L' (1, 1, 0, 1), \quad (3)$$

where the first two numbers refer to the representation. The scalar fields can be written as above with a tilde on them except that $\tilde{E}_L^c = \tilde{E}_R^*$, $\tilde{E}'^c = \tilde{E}_R'^*$. We also here note that the Higgs doublets in the MSSM have the quantum numbers

$$H_d = (\mathbf{1}, \mathbf{2}, -\frac{1}{2}, 0), \quad H_u = (\mathbf{1}, \mathbf{2}, +\frac{1}{2}, 0). \quad (4)$$

Here we also note that all of the MSSM particles carry no $U(1)_X$ charge. The superpotential for the vectorlike leptonic supermultiplets is given by

$$W = y L H_d E_L^c + y' L'^c H_u E_L' + M_L L L'^c + M_E E_L' E_L^c + M_N N_L' N_L^c, \quad (5)$$

where M_L , M_E and M_N are the vectorlike masses. After spontaneous breaking the two Higgs doublets of $SU(2)_L$ develop VEVs so that:

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix} = \begin{pmatrix} \frac{1}{\sqrt{2}}(v_d + \phi_1) \\ H_d^- \end{pmatrix}, \quad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} = \begin{pmatrix} H_u^+ \\ \frac{1}{\sqrt{2}}(v_u + \phi_2) \end{pmatrix}, \quad (6)$$

where v_d and v_u are the VEVs of H_d^0 and H_u^0 . Now ρ couples only to the scalars so we focus on the scalar fields which are charged under $U(1)_X$. In this case we have a 4×4 mass squared matrix and in the basis $(\tilde{E}_L, \tilde{E}_R, \tilde{E}_L', \tilde{E}_R')$ it is given by ⁴

$$\frac{1}{\sqrt{2}} \left(\begin{array}{cc|cc} \sqrt{2}(M_E^2)_{2 \times 2} & & y'v_u M_L + yv_d M_E & 0 \\ & & 0 & y'v_u M_E + yv_d M_L \\ \hline y'v_u M_L + yv_d M_E & 0 & \sqrt{2}(M_{E'}^2)_{2 \times 2} & \\ 0 & y'v_u M_E + yv_d M_L & & \end{array} \right)_{4 \times 4}. \quad (7)$$

Here $(M_E^2)_{2 \times 2}$ is given by

$$(M_E^2)_{2 \times 2} = \begin{pmatrix} M_1^2 + \frac{1}{2}y^2 v_d^2 + M_L^2 + \frac{(g_1^2 - g_2^2)}{8}(v_d^2 - v_u^2) & \frac{1}{\sqrt{2}}y(A_E v_d - \mu v_u) \\ \frac{1}{\sqrt{2}}y(A_E v_d - \mu v_u) & M_1^2 + \frac{1}{2}y^2 v_d^2 + M_E^2 - \frac{g_1^2}{4}(v_d^2 - v_u^2) \end{pmatrix}, \quad (8)$$

⁴ In the analysis below the 2×2 off-diagonal matrices in Eq. (7) will be neglected. They are displayed in Eq. (7) for completeness.

where M_1 is the soft mass while M_L and M_E are vectorlike masses. We label the eigenvalues as $m_{\tilde{E}_1}^2$ and $m_{\tilde{E}_2}^2$ and the corresponding eigenstates by \tilde{E}_1 and \tilde{E}_2 which are related to \tilde{E}_L and \tilde{E}_R by

$$\begin{pmatrix} \tilde{E}_L \\ \tilde{E}_R \end{pmatrix} = \begin{pmatrix} \cos \xi & \sin \xi \\ -\sin \xi & \cos \xi \end{pmatrix} \begin{pmatrix} \tilde{E}_1 \\ \tilde{E}_2 \end{pmatrix} . \quad (9)$$

Similarly $(M_{\tilde{E}'}^2)_{2 \times 2}$ is given by

$$(M_{\tilde{E}'}^2)_{2 \times 2} = \begin{pmatrix} M_2^2 + \frac{1}{2}y'^2 v_u^2 + M_L^2 - \frac{(g_1^2 - g_2^2)}{8}(v_d^2 - v_u^2) & \frac{1}{\sqrt{2}}y'(A_{E'}v_u - \mu v_d) \\ \frac{1}{\sqrt{2}}y'(A_{E'}v_u - \mu v_d) & M_2^2 + \frac{1}{2}y'^2 v_u^2 + M_E^2 + \frac{g_1^2}{4}(v_d^2 - v_u^2) \end{pmatrix} \quad (10)$$

where M_2 is the soft mass. We label the eigenvalues of this mass squared matrix by $m_{\tilde{E}'_1}^2, m_{\tilde{E}'_2}^2$ with the corresponding eigenstates as \tilde{E}'_1 and \tilde{E}'_2 . They are related to \tilde{E}'_L and \tilde{E}'_R by

$$\begin{pmatrix} \tilde{E}'_L \\ \tilde{E}'_R \end{pmatrix} = \begin{pmatrix} \cos \xi' & \sin \xi' \\ -\sin \xi' & \cos \xi' \end{pmatrix} \begin{pmatrix} \tilde{E}'_1 \\ \tilde{E}'_2 \end{pmatrix} . \quad (11)$$

Since the diagonalization of the 4×4 scalar mass squared matrix is intractable, we consider the case where the product of the fermion masses and the vectorlike masses are much smaller than the soft mass squares. In this case the mass squared matrix of Eq. (7) takes on a block diagonal form where the 2×2 matrix in the upper left hand corner is the mass squared matrix for the normal leptons in the vectorlike multiplet and the 2×2 matrix in the lower right hand corner is the mass squared matrix for the mirror leptons in the vector like multiplet.

In the analysis we have a $U(1)_X$ extension of MSSM and we assume that $U(1)_X$ gauge boson acquires mass through a Stueckelberg mechanism. This mechanism works only for $U(1)$ extensions. To achieve the extension we need to include a vector superfield C and scalar supefields S and \bar{S} and assume a Lagrangian of the type

$$\mathcal{L}_{\text{St}} = \int d\theta^2 d\bar{\theta}^2 [M_C C + S + \bar{S}]^2 , \quad (12)$$

The Lagrangian is invariant under the $U(1)_X$ gauge transformations

$$\delta_X C = \Lambda_X + \bar{\Lambda}_X , \quad \delta_X S = -M_C \Lambda_X . \quad (13)$$

The vector superfield C in Wess-Zumino gauge is given by

$$C = -\theta\sigma^\mu\bar{\theta}C_\mu + i\theta\theta\bar{\theta}\bar{\lambda}_C - i\bar{\theta}\bar{\theta}\theta\lambda_C + \frac{1}{2}\theta\theta\bar{\theta}\bar{\theta}D_C , \quad (14)$$

while S is given by

$$S = \frac{1}{2}(\rho + ia) + \theta\chi + i\theta\sigma^\mu\bar{\theta}\frac{1}{2}(\partial_\mu\rho + i\partial_\mu a) \quad (15)$$

$$+ \theta\theta F + \frac{i}{2}\theta\theta\bar{\theta}\bar{\sigma}^\mu\partial_\mu\chi + \frac{1}{8}\theta\theta\bar{\theta}\bar{\theta}(\Box\rho + i\Box a) .$$

The complex scalar component of S contains the axionic pseudo-scalar a and a real scalar field ρ . \mathcal{L}_{St} in component notation takes the form

$$\begin{aligned} \mathcal{L}_{\text{St}} = & -\frac{1}{2}(MC_\mu + \partial_\mu a)^2 - \frac{1}{2}(\partial_\mu \rho)^2 - i\chi\sigma^\mu\partial_\mu\bar{\chi} + 2|F|^2 \\ & + M\rho D_C + M\bar{\chi}\bar{\lambda}_C + M\chi\lambda_C . \end{aligned} \quad (16)$$

For the gauge field we add the kinetic terms

$$\mathcal{L}_{\text{gkin}} = -\frac{1}{4}C_{\mu\nu}C^{\mu\nu} - i\lambda_C\sigma^\mu\partial_\mu\bar{\lambda}_C + \frac{1}{2}D_C^2 \quad (17)$$

where $C_{\mu\nu} = \partial_\mu C_\nu - \partial_\nu C_\mu$. For the matter fields (i.e., hidden sector matter) chiral superfields with components (f_i, z_i, F_i) are introduced, which are defined similar to S . Their Lagrangian is standard and we do not display it here. It is the real scalar field ρ which is the focus of our study here. From Eq.(16) and Eq.(17) it is seen that the mass of C_μ which is identified in the unitary gauge as Z' is the same as the mass of ρ which can be gotten by elimination of the auxiliary field D_C .

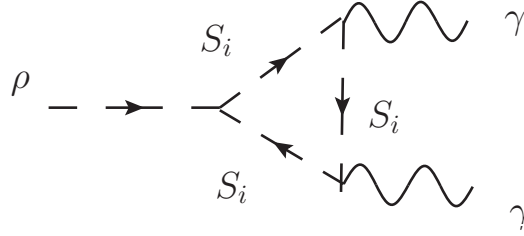


Figure 1: Triangle loop diagram for the decay process $\rho \rightarrow \gamma\gamma$ via exchange of vectorlike scalars (arising from Eq. (2) and Eq. (3)) in the loop which are charged under $U(1)_X$ and under $U(1)_{\text{em}}$.

3 ρ lifetime

We use the interactions of appendix A to compute the ρ lifetime. The decay width of ρ through scalar loops is given by (see, e.g., [19])

$$\Gamma(\rho \rightarrow \gamma\gamma) = \frac{\alpha^2 m_\rho^3}{1024\pi^3} \left[\sum_i \frac{g_{\rho S_i S_i}}{m_{S_i}^2} N_{C,S} q_{S_i}^2 A_0(\tau_{s_i}) \right]^2 , \quad (18)$$

Here the explicit form of $g_{\rho S_i S_i}$, where S_i are in the mass diagonal basis, is given in appendix A. In Eq. (18) $N_{C,S}$ are the (color, spin) multiplicities and q_{S_i} is the electric charge for the field S_i

under $U(1)_{\text{em}}$. We note that ρ does not couple with the particles in the standard model, i.e., with quarks and leptons, or with the Higgs or with W^\pm so these particles cannot appear in the loop. Only the scalars charged under $U(1)_X$ and under $U(1)_{\text{em}}$ can appear in the loop. In Eq. (18) $\alpha = 1/137$, $m_\rho = 7 \text{ keV} = 7 \times 10^{-6} \text{ GeV}$, where τ_s is defined by $\tau_s = \frac{4m_S^2}{m_\rho^2}$. $A_0(\tau)$ that appears in Eq.(18) is a loop function which is given by

$$A_0(\tau) = -\tau[1 - \tau f(\tau)] , \quad (19)$$

where $f(\tau)$ is defined by

$$f(\tau) = \begin{cases} \left(\arcsin \frac{1}{\sqrt{\tau}} \right)^2, & \tau \geq 1 , \\ -\frac{1}{4} \left[\ln \frac{\eta_+}{\eta_-} - i\pi \right]^2, & \tau < 1 , \end{cases} \quad (20)$$

where $\eta_\pm \equiv (1 \pm \sqrt{1 - \tau})$ and $\tau = 4m^2/m_\rho^2$ for a particle running in the loop with mass m . For the case when $\tau \gg 1$ one has

$$f(\tau) \rightarrow \frac{1}{\tau} \left(1 + \frac{1}{3\tau} + \dots \right), \quad (21)$$

and in this limit $A_0 \rightarrow 1/3$. For our case $\tau \gg 1$ so we can replace A_0 by $1/3$. Next using the result of appendix A we have

$$\sum_i \frac{g_{\rho S_i S_i}}{m_{S_i}^2} N_{C,S} q_{S_i}^2 A_0(\tau_{s_i}) = g_X q_E^2 Q_E \cos 2\xi \frac{m_\rho}{3m_S^2} + g_X q_{E'}^2 Q_{E'} \cos 2\xi' \frac{m_\rho}{3m_{S'}^2} . \quad (22)$$

Here we have set $A_0 = 1/3$, and m_S^2 and $m_{S'}^2$ are effective scalar mass squares defined by

$$m_S^2 = \frac{m_{\tilde{E}_1}^2 m_{\tilde{E}_2}^2}{m_{\tilde{E}_2}^2 - m_{\tilde{E}_1}^2}, \quad m_{S'}^2 = \frac{m_{\tilde{E}'_1}^2 m_{\tilde{E}'_2}^2}{m_{\tilde{E}'_2}^2 - m_{\tilde{E}'_1}^2}, \quad (23)$$

where $m_{\tilde{E}_1}$ and $m_{\tilde{E}_2}$ are mass eigenvalues corresponding to the eigenstates \tilde{E}_1 and \tilde{E}_2 etc. The width formula now simplifies to

$$\Gamma(\rho \rightarrow \gamma\gamma) = \frac{\alpha^2 m_\rho^5 g_X^2}{9 \times 1024 \pi^3} \left(\frac{Q_E \cos 2\xi}{m_S^2} + \frac{Q_{E'} \cos 2\xi'}{m_{S'}^2} \right)^2, \quad (24)$$

where we have used $q_E = q_{E'} = 1$. A numerical analysis of $\Gamma(\rho \rightarrow \gamma\gamma)$ along with the relic density constraint will be discussed in Section 5.

4 Relic density analysis

4.1 The decay $H^0 \rightarrow h^0 + \rho$

The H^0 decays into $h^0 + \rho$ via triangle loops and there are $4^3 = 64$ triangle loops to consider. Here we neglect the mixing due to the off diagonal terms in Eq. (7), and only consider 16 different triangle

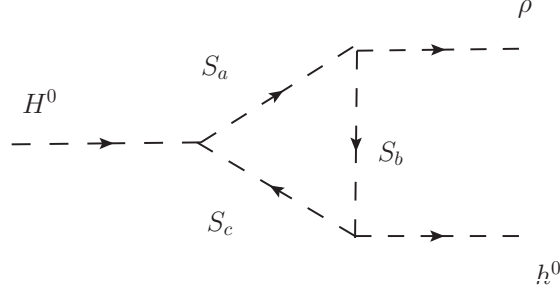


Figure 2: Triangle loop diagram for the decay process $H^0 \rightarrow \rho + h^0$ via exchange of vectorlike scalars (arising from Eq. (2) and Eq. (3)) in the loop which are charged under $U(1)_X$.

diagrams. The reduction from 64 to 16 is due to the neglect of the off diagonal terms in Eq. (7). Thus in a compact notation we can write the interaction of ρ with the scalars charged under $U(1)_X$ as

$$\mathcal{L}_{\text{st}} = m_\rho g_X Q_E \rho g_{\rho ij} \tilde{E}_i^* \tilde{E}_j + m_\rho g_X Q_{E'} \rho g'_{\rho ij} \tilde{E}_i'^* \tilde{E}_j' , \quad i, j = 1, 2 \quad (25)$$

where $g_{\rho ij}$ and $g'_{\rho ij}$ are the “reduced” couplings and are given by (along with other couplings to the Higgses)

$$g_{\rho 11} = -g_{\rho 22} = g_{h12} = g_{h21} = g_{H12} = g_{H21} = \cos 2\xi , \quad (26)$$

$$g_{\rho 12} = g_{\rho 21} = -g_{h11} = g_{h22} = -g_{H11} = g_{H22} = \sin 2\xi , \quad (27)$$

$$g'_{\rho 11} = -g'_{\rho 22} = g'_{h12} = g'_{h21} = g'_{H12} = g'_{H21} = \cos 2\xi' , \quad (28)$$

$$g'_{\rho 12} = g'_{\rho 21} = -g'_{h11} = g'_{h22} = -g'_{H11} = g'_{H22} = \sin 2\xi' . \quad (29)$$

Let us consider the g_{ij} couplings. Since each scalar propagator can be either \tilde{E}_1 or \tilde{E}_2 , there are eight different triangle diagrams that contribute. For a specific diagram labeled by the three scalars in the loop as (a, b, c) , as shown in Fig. (2), the matrix element is given by

$$\mathcal{M}_{abc} = G_0 g_{\rho ab} g_{hbc} g_{Hca} I_{abc} \quad (30)$$

where

$$G_0 \equiv m_\rho g_X Q_E \left(\frac{g_2 m_E}{2M_W \cos \beta} \right)^2 (-A_E \sin \alpha + \mu \cos \alpha)(A_E \cos \alpha + \mu \sin \alpha) , \quad (31)$$

and

$$I_{abc} \equiv \int \frac{d^4 k}{(2\pi)^4} \left[\frac{1}{(k + p_2)^2 - m_a^2} \frac{1}{k^2 - m_b^2} \frac{1}{(k - p_3)^2 - m_c^2} \right] . \quad (32)$$

Using Feynman parameterization, we obtain the loop integral as

$$I_{abc} = \frac{-i}{(4\pi)^2} \frac{1}{B_2} \int_0^1 dx \left[f \left(\frac{B_1}{2B_2} + 1 - x, A \right) - f \left(\frac{B_1}{2B_2}, A \right) \right] , \quad (33)$$

where

$$B_0 \equiv x^2 m_\rho^2 + x(m_a^2 - m_b^2 - m_\rho^2) + m_b^2, \quad (34)$$

$$B_1 \equiv m_c^2 - m_b^2 - m_{h^0}^2 - x(m_{H^0}^2 - m_\rho^2 - m_{h^0}^2), \quad (35)$$

$$B_2 \equiv m_{h^0}^2, \quad (36)$$

$$A \equiv \frac{4B_0 B_2 - B_1^2}{4B_2^2}, \quad (37)$$

and the function $f(x, A)$ is defined as

$$f(x, A) \equiv \frac{1}{\sqrt{|A|}} \begin{cases} \arctan(x/\sqrt{A}); & A > 0 \\ \ln \sqrt{\frac{x-\sqrt{-A}}{x+\sqrt{-A}}}; & A < 0. \end{cases} \quad (38)$$

The total matrix element is then given by

$$\mathcal{M} = G_0 \sum_{a,b,c} (g_{\rho ab} g_{hbc} g_{Hca} I_{abc}). \quad (39)$$

Summing over all possibilities, we have

$$\mathcal{M}/G_0 = c^3(I_{112} - I_{221}) + cs^2(I_{111} - I_{121} + I_{122} - I_{211} + I_{212} - I_{222}), \quad (40)$$

where $c \equiv \cos(2\xi)$ and $s \equiv \sin(2\xi)$. The decay width of the process $H^0 \rightarrow h^0 + \rho$ can now be computed

$$\Gamma(H^0 \rightarrow h^0 + \rho) = \frac{1}{16\pi m_{H^0}} \left[1 - \left(\frac{m_{h^0}}{m_{H^0}} \right)^2 \right] |\overline{\mathcal{M} + \mathcal{M}'^2}|. \quad (41)$$

where \mathcal{M}' is the amplitude with g_{ij} replaced by g'_{ij} , and G_0 replaced with G'_0 which is given by

$$G'_0 \equiv m_\rho g_X Q_{E'} \left(\frac{g_2 m_{E'}}{2M_W \sin \beta} \right)^2 (A_{E'} \sin \alpha + \mu \cos \alpha)(A_{E'} \cos \alpha - \mu \sin \alpha). \quad (42)$$

The relic density analysis is similar to that of [3]. With the following variables

$$z \equiv \frac{m_{H^0}}{T}, f_\rho \equiv \frac{n_\rho}{T^3}, f_{H^0} \equiv \frac{n_{H^0}}{T^3}, K \equiv \frac{1.66\sqrt{g_*}}{m_{\text{Pl}}}, \quad (43)$$

In the above m_{H^0} is the mass of the heavy neutral Higgs, n_{H^0} is its number density, n_ρ is the number density of ρ , and g_* is the entropy degrees of freedom. Further, T is the temperature of the thermal bath, $H = KT^2$ is the Hubble constant, $m_{\text{Pl}} = 1.22 \times 10^{19}$ GeV is the Planck mass, we obtain neglecting the back reaction⁵

$$\frac{df_\rho(z)}{dz} = \frac{\langle \Gamma(H^0 \rightarrow h^0 + \rho) \rangle}{Km_{H^0}^2} z f_{H^0}(z). \quad (44)$$

⁵The neglect of the back reaction is justified since the number density of ρ is small.

The thermal average on the decay width is $\langle \Gamma \rangle = \Gamma K_1(z)/K_2(z)$ where $K_{1,2}(z)$ are the modified Bessel functions, and $f_{H^0}(z) = z^2 K_2(z)/(2\pi^2)$ (assuming Maxwell-Boltzmann statistics), so we have

$$f_\rho(z) = \frac{\Gamma(H^0 \rightarrow h^0 + \rho)}{K m_{H^0}^2} \int_{z'=z_0}^z dz' K_1(z') \frac{z'^3}{2\pi^2} , \quad (45)$$

where $z_0 = m_{H^0}/T_{\text{EW}}$ with T_{EW} being the electroweak phase transition temperature, and we neglected the temperature dependence of K . For the case where $m_{H^0} = 500$ GeV and $T_{\text{EW}} = 300$ GeV, the above integral gives an asymptotic value ~ 0.2 for $z > 10$. Thus we obtain (for $m_{H^0} = 500$ GeV)

$$f_\rho(z > 10) \simeq \frac{0.2 \times \Gamma(H^0 \rightarrow h^0 + \rho)}{K m_{H^0}^2} . \quad (46)$$

The quantity n_ρ/s is conserved after H^0 disappears in the plasma, where s is the entropy density. The current dark matter number density is then given by

$$n_\rho^0 = (T_0)^3 \frac{g_{*s}^0}{g_{*s}^{\text{freeze-out}}} f_\rho(z = 20) = (T_0)^3 \frac{g_{*s}^0}{g_{*s}^{\text{freeze-out}}} \frac{0.2 \times \Gamma(H^0 \rightarrow h^0 + \rho)}{K m_{H^0}^2} , \quad (47)$$

where $T_0 = 2.73$ K, $g_{*s}^0 = 3.91$ is the current degree of freedom, and $g_{*s}^{\text{freeze-out}}$ is the degree of freedom during freeze out so that $g_{*s}^{\text{freeze-out}} = g_{*s}(T \simeq m_{H^0}/20)$. The relic density due to H^0 decay is thus given by

$$\Omega_\rho h^2 = \frac{n_\rho^0 m_\rho}{\rho_c} h^2 \simeq \frac{n_\rho^0 m_\rho}{8 \times 10^{-47} \text{ GeV}^{-4}} . \quad (48)$$

4.2 $\tilde{E}_1 + \tilde{\bar{E}}_1 \rightarrow \rho + h^0$

The dark matter can also be generated via scalar annihilations. We first discuss \tilde{E} scalar annihilation. Among the two possible final states $\rho + h^0$ and $\rho + \rho$, the $\rho + \rho$ final state is suppressed by a factor of m_ρ^4 . Thus we compute the matrix element for $\tilde{E}_1 + \tilde{\bar{E}}_1 \rightarrow \rho + h^0$ as shown in Fig. (3). Here we find

$$(v_{\text{rel}} \sigma) = \frac{A}{s(s - m_{h^0}^2)} , \quad (49)$$

where

$$A \equiv \left[m_\rho g_X Q_E \frac{g_2 m_E}{4 M_W \cos \beta} (-A_E \sin \alpha + \mu \cos \alpha) \sin(4\xi) \right]^2 \frac{1}{8\pi m_{\tilde{E}_1}^2} . \quad (50)$$

The DM number density due to the annihilation process is given via the following Boltzmann equation (neglecting the initial DM density)

$$\dot{n}_\rho + 3H n_\rho = n_{\tilde{E}_1}^2 \langle v_{\text{rel}} \sigma \rangle . \quad (51)$$

Defining the variables $z \equiv m_{\tilde{E}_1}/T$, $f_{\tilde{E}_1} \equiv n_{\tilde{E}_1}/T^3$ (see [3]) we obtain

$$\frac{df_\rho}{dz} = \frac{m_{\tilde{E}_1} f_{\tilde{E}_1}^2}{K z^2} \langle v_{\text{rel}} \sigma \rangle . \quad (52)$$

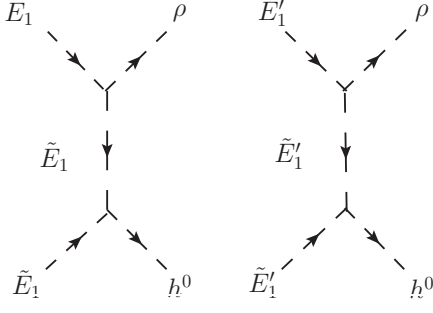


Figure 3: Feynman diagrams for the process $\tilde{E}_1(\tilde{E}'_1) + \tilde{E}_1(\tilde{E}'_1) \rightarrow \rho + h^0$.

The thermal average of the annihilation is given by

$$\langle v_{\text{rel}} \sigma \rangle = \frac{1}{16T m_{\tilde{E}_1}^4 K_2^2(z)} \int_{4m_{\tilde{E}_1}^2}^{\infty} s \sqrt{s - 4m_{\tilde{E}_1}^2} K_1(\sqrt{s}/T) \langle v_{\text{rel}} \sigma \rangle ds . \quad (53)$$

Thus we obtain

$$\begin{aligned} f_\rho &= \frac{A}{64\pi^4 m_{\tilde{E}_1}^4 K} \int_1^{20} dz z^3 \int_{4m_{\tilde{E}_1}^2}^{\infty} ds \frac{\sqrt{s - 4m_{\tilde{E}_1}^2}}{s - m_h^2} K_1(\sqrt{s}z/m_{\tilde{E}_1}) \\ &\equiv \frac{A}{64\pi^4 m_{\tilde{E}_1}^4 K} F(m_{\tilde{E}_1}) , \end{aligned} \quad (54)$$

where we have used $f_{\tilde{E}_1} = z^2 K_2(z)/(2\pi^2)$ ⁶. The 2-D integral only depends on the scalar mass $m_{\tilde{E}_1}$, and we found that the relation $F(m_{\tilde{E}_1}) \simeq 0.115 m_{\tilde{E}_1}$ can nicely approximate the integral for a large mass range, $m_{\tilde{E}_1} \in (10^2, 10^7)$ GeV. The relic density calculation is similar to the decay process as discussed in Section 4.1, once f_ρ is known at \tilde{E}_1 freeze-out. Thus we obtain the relic density due to annihilation

$$\begin{aligned} (\Omega_\rho h^2)_{\text{ann}} &= \frac{m_\rho}{8 \times 10^{-47} \text{ GeV}^{-4}} (T^0)^3 \frac{g_{*s}^0}{g_{*s}^{\text{freeze-out}}} \frac{A}{64\pi^4 m_{\tilde{E}_1}^4 K} 0.115 m_{\tilde{E}_1} \\ &= 6 \times 10^{14} \text{ GeV} \frac{A}{m_{\tilde{E}_1}^3} . \end{aligned} \quad (55)$$

Similarly, one can compute the ρ relic density due to the \tilde{E}'_1 annihilations. For the \tilde{E}'_1 annihilations, the quantity $(A/m_{\tilde{E}_1}^3)$ here has to be replaced by $(A'/m_{\tilde{E}'_1}^3)$ where A' is given by

$$A' \equiv \left[m_\rho g_X Q_{E'} \frac{g_2 m_{E'}}{4M_W \sin \beta} (A_{E'} \cos \alpha - \mu \sin \alpha) \sin(4\xi') \right]^2 \frac{1}{8\pi m_{\tilde{E}'_1}^2} . \quad (56)$$

⁶For scalar mass higher than the electroweak phase transition temperature $T_{\text{EW}} = 300$ GeV, the integral should start at $z = m_{\tilde{E}_1}/T_{\text{EW}}$. In this case using $z = 1$ for the lower end of the integral overestimates the contribution due to scalar annihilations. However, as shown later, the scalar annihilation is subdominant to the H^0 decay process for the parameter space of interest and is negligible in any case for the parameter space of interest.

5 Numerical Analysis

To fit the experimental data Eq. (1) we need to compute the lifetime and the relic density of the ρ . This is done by carrying out a scan in the parameter space where we take the ranges of the soft masses M_1, M_2 , of the vectorlike masses M_L, M_E , of the trilinear couplings $A_E, A_{E'}$ and of the fermion masses $m_E, m_{E'}$ generated by Yukawa couplings in the following ranges

$$(M_1, M_2, M_L, M_E, A_E, A_{E'}, \mu) \in (10^2, 10^5) \text{ GeV}, \quad (57)$$

$$m_E \in (100, 246) \text{ GeV}, m_{E'} \in (100, 300) \text{ GeV} . \quad (58)$$

where m_E and $m_{E'}$ are defined so that

$$m_E \equiv \frac{1}{\sqrt{2}} y v_d, \quad m_{E'} \equiv \frac{1}{\sqrt{2}} y' v_u . \quad (59)$$

Further we require that $y < 2$ and $y' < 2$, which put constraints on the $\tan\beta$ value such that $\pi/4 < \beta < \arccos(m_E/(\sqrt{2}v))$. We also take $g_X = 1$, $m_{H^0} = 500 \text{ GeV}$, $m_{h^0} = 125 \text{ GeV}$, $m_\rho = 7 \text{ keV}$, and $\alpha = \beta - \pi/2$ (see e.g., [20]). We investigate the possibility that the dark matter constituted by ρ contributes only a fraction of the relic density for dark matter measured by WMAP which is $\Omega_{\text{WMAP}} h^2 \simeq 0.11$ [21]. Thus a desirable range is $R \equiv \Omega_\rho/\Omega_{\text{DM}} \in (0.01, 0.1)$. This would leave the other major component to be the neutralino for which the dark matter searches can be pursued in the direct and the indirect detection experiments. In the analysis of the relic density of ρ we include all the allowed processes. As discussed in Section 4 and in appendix B the following processes contribute to the relic density

$$H^0 \rightarrow h^0 + \rho , \quad (60)$$

$$\tilde{E}_1 + \bar{\tilde{E}}_1 \rightarrow \rho + h^0 , \quad (61)$$

$$\tilde{E}'_1 + \bar{\tilde{E}}'_1 \rightarrow \rho + h^0 . \quad (62)$$

In addition there are other processes which are highly suppressed such as decays and annihilations with 2ρ final states. We have computed the processes listed above. Of these the one which produces the dominant component of the ρ relic density is the process $H^0 \rightarrow h^0 + \rho$ while the other processes are subdominant. Thus the annihilation processes involving $\tilde{E}_1 + \bar{\tilde{E}}_1$ and $\tilde{E}'_1 + \bar{\tilde{E}}'_1$ together contribute at most 1% of the number density of ρ , in the parameter space of interest. An analysis of the ρ lifetime vs R is given in Fig. 4. Here one finds that there exist parameter choices which fit the data on the 3.5 keV emission line with ρ being a subdominant component of the total relic density. Thus with ρ constituting (1-10)% of the relic density or even less it is possible to satisfy the constraint of Eq. (1). In Table 1 we exhibit a set of parameter points satisfying the relic density constraint

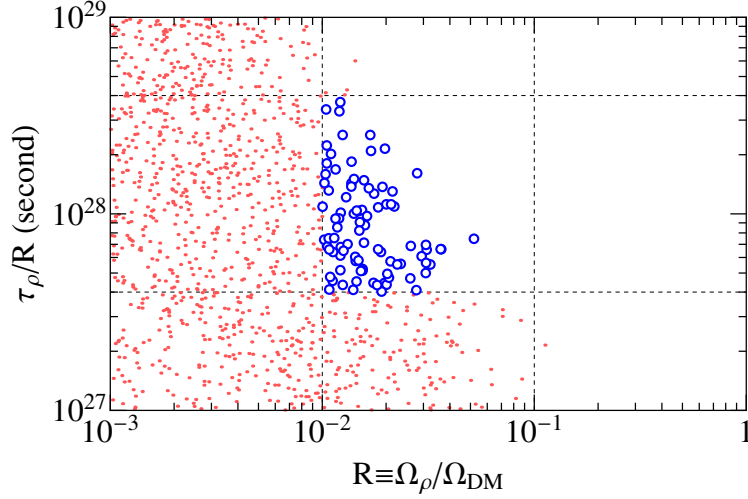


Figure 4: Blue circles: 90 models out of the 2×10^5 random scans in the parameter space satisfying the constraints $R \equiv \Omega_\rho/\Omega_{DM} \in (0.01, 0.1)$ and $\tau_\rho/R \in 4 \times (10^{27}, 10^{28})$ s. Red points: generic model points in the parameter space.

discussed above and satisfying the constraint of Eq. (1). It is interesting to ask what the impact is of this two component dark matter model with (1-10)% of dark matter constituted of ρ and the rest made up of neutralinos on the direct detection of dark matter. The main impact is on the comparison of theory with experiment. Thus one compares the theoretical value $r\sigma_{\chi_1^0 p}^{SI}$ where $r = \Omega_{\chi_1^0} h_0^2 / \Omega_{DM} h_0^2$ with experiment. For $r = 0.9 - 0.99$, the theoretical predictions will be smaller by a factor of 0.9-0.99 which means that some of the parameter points that were eliminated by the current upper limits are still viable. So effectively inclusion of a second dark matter component increases the allowed parameter space of SUSY models and thus relaxes the dark matter constraints from the direct detection of dark matter on these models.

We note in passing that the Stueckelberg model will have a Z' which if stable will contribute to the dark matter density like the ρ . However, unlike the ρ it cannot decay into two photons. Further, it has no couplings to the standard model particles. To circumvent this problem and allow Z' to decay we can generate a small mixing between $U(1)_X$ and a gauged $L_\mu - L_\tau$ (see, e.g., [16]) allowing the Z' to have a tiny coupling to the muon and to the tau neutrinos which permits the decays $Z' \rightarrow \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau$. On the other hand ρ cannot couple to fermions and thus such decays are not allowed for the ρ and the ρ can only have photonic decays. We also note that after $Z' - Z''$ mixing where Z'' is the gauge boson of $L_\mu - L_\tau$ which also acquires a mass via the Stueckelberg mechanism, the new leptons can annihilate to the standard model particles via the Z', Z'' poles. Thus specifically we will have annihilation processes such as $E' \bar{E}' \rightarrow Z'' \rightarrow \nu_\mu \bar{\nu}_\mu, \nu_\tau \bar{\nu}_\tau, \mu \bar{\mu}, \tau \bar{\tau}$ which

deplete the matter density of the new leptons by resonant annihilation if the mass of the Z'' is chosen to be in the vicinity of twice the mass of the new leptons. The analysis is similar to the one given in [12]. Further, we give soft masses to the $U(1)_X$ and $U(1)_{L_\mu-L_\tau}$ gauginos which are large enough so they can decay into the MSSM fields. Thus for $U(1)_X$ the coupling $\tilde{E}'\lambda\tilde{E}'$ would decay λ into E' and \tilde{E}' which in turn will annihilate to the MSSM particles as discussed above.

Model	M_1	M_2	M_L	M_E	m_E	$m_{E'}$	A_E	$A_{E'}$	μ	$\tan\beta$
A	4.21e3	2.55e3	3.05e2	2.02e2	1.73e2	1.59e2	4.32e4	1.06e2	6.06e4	1.47
B	6.24e3	3.53e3	2.43e3	1.72e2	1.98e2	1.57e2	6.44e4	9.81e3	7.73e4	1.00
C	3.17e4	5.07e3	8.43e2	3.72e3	1.03e2	2.79e2	1.01e4	8.88e4	7.07e2	1.61
D	6.21e3	4.65e3	1.48e3	4.24e3	2.19e2	2.33e2	3.59e3	8.54e4	1.15e4	1.06
E	4.88e4	2.65e3	1.05e3	1.41e3	2.06e2	1.41e2	1.15e2	4.62e2	6.45e4	1.17

Model	$m_{\tilde{E}_1}$	$m_{\tilde{E}_2}$	$m_{\tilde{E}'_1}$	$m_{\tilde{E}'_2}$	$\Omega_\rho^{H^0}/\Omega_{\text{DM}}$	$\Omega_\rho^{\tilde{E}_1}/\Omega_{\text{DM}}$	$\Omega_\rho^{\tilde{E}'_1}/\Omega_{\text{DM}}$	τ_ρ/R (s)
A	3.2e3	5.1e3	2.9e2	3.6e3	2.0e-2	3.0e-9	6.0e-5	4.4e27
B	6.2e3	6.8e3	2.1e3	5.1e3	1.2e-2	3.6e-6	4.8e-5	6.1e27
C	3.2e4	3.2e4	2.8e3	7.7e3	3.6e-2	1.3e-13	4.0e-5	6.6e27
D	6.4e3	7.5e3	3.6e3	7.1e3	1.4e-2	9.5e-9	2.0e-5	1.5e28
E	4.9e4	4.9e4	9.2e2	4.0e3	1.1e-2	1.2e-13	4.9e-5	4.8e27

Table 1: Candidate models: A, B, C, D, and E. All the masses are in GeV. The quantities $\Omega_\rho^{H^0}$, $\Omega_\rho^{\tilde{E}_1}$, and $\Omega_\rho^{\tilde{E}'_1}$ are the contributions to the ρ relic density due to the decay process $H^0 \rightarrow h^0 + \rho$, and the annihilation processes $\tilde{E}_1 + \tilde{\bar{E}}_1 \rightarrow \rho + h^0$ and $\tilde{E}'_1 + \tilde{\bar{E}}'_1 \rightarrow \rho + h^0$. Ω_{DM} is the total dark matter density which is taken to be $\Omega_{\text{DM}}h^2 = 0.11$ and τ_ρ is the dark matter lifetime. R is the ratio between the relic density of the ρ dark matter and the total dark matter.

6 Conclusion

In this work we have given an analysis of the 3.5 keV emission line emanating from galaxy clusters as seen by two experiments. A possible explanation of the monochromatic nature of the radiation is that it originates from the decay of a 7 keV particle. In this work we identify this particle as a scalar ρ that appears in a supersymmetric $U(1)_X$ Stueckelberg extension of models with the standard model gauge group. In such an extension, the ρ couples only to scalar fields that carry a $U(1)_X$ quantum number. The proposed $U(1)_X$ extension contains vectorlike multiplets which are charged under $SU(2)_L \times U(1)_Y$ as well as under $U(1)_X$. Thus the scalars of the vectorlike multiplet couple to ρ as well as to the Higgs field and to the photon. These vectorlike couplings allow the decay of the ρ to two photons via triangle loops involving scalar particles. An important constraint on the lifetime of the ρ arises from the fraction that ρ contributes to the dark matter relic density. The relic density of the ρ arises only after electroweak symmetry breaking. Thus below the electroweak

symmetry breaking scale the CP even Higgses can decay to a ρ and there are various decay channels such as $h^0 \rightarrow \rho + \rho$, $H^0 \rightarrow \rho + h^0$, $H^0 \rightarrow \rho + \rho$. Additionally annihilation can contribute to the relic density such as via the process $\tilde{E}_1 + \tilde{\bar{E}}_1 \rightarrow h^0 + \rho$ and the process $\tilde{E}'_1 + \tilde{\bar{E}}'_1 \rightarrow h^0 + \rho$. However, the dominant process that contributes to the relic density turns out to be $H^0 \rightarrow \rho + h^0$. A simultaneous analysis of the relic density and of the ρ lifetime is needed to fit the data. In the analysis presented in this work we are able to fit the data with ρ as a subdominant component of dark matter. Thus we have a multicomponent dark matter model where the emission line arises from a 7 keV scalar particle while the rest is constituted of neutralino dark matter which can be detected in direct detection experiments such as XENON1T [22], SuperCDMS [23] and LUX [24]. Finally we note that our mechanism for generating a 3.5 keV line as well as the implications of the model are very different from other models that have recently been proposed [2–5, 25–54].

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A Interactions of the vectorlike multiplet

We discuss now the interactions that are needed for the analysis in this work using the results of [7, 55, 56]. The photonic interactions are given by

$$\mathcal{L}_\gamma = iq_E e (\tilde{E}_L^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}_L + \tilde{E}_R^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}_R) A^\mu + iq_{E'} e (\tilde{E}'_L^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}'_L + \tilde{E}'_R^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}'_R) A^\mu, \quad (63)$$

where $q_E = q_{E'} = 1$. The interactions of h^0/H^0 with the charged particles of the vector multiplet are given by (see, e.g., [56], Eq. (4.19))

$$\mathcal{L}_{EEh^0/H^0} = -\frac{g_2 m_E}{2M_W \cos \beta} (\tilde{E}_R^* \tilde{E}_L + \tilde{E}_L^* \tilde{E}_R) [(A_E \cos \alpha + \mu \sin \alpha) H^0 + (-A_E \sin \alpha + \mu \cos \alpha) h^0], \quad (64)$$

$$\mathcal{L}_{E'E'h^0/H^0} = -\frac{g_2 m_{E'}}{2M_W \sin \beta} (\tilde{E}'_R^* \tilde{E}'_L + \tilde{E}'_L^* \tilde{E}'_R) [(A_{E'} \sin \alpha + \mu \cos \alpha) H^0 + (A_{E'} \cos \alpha - \mu \sin \alpha) h^0], \quad (65)$$

where α is the Higgs mixing angle defined by

$$H_d^1 = \frac{1}{\sqrt{2}} [v_d + H^0 \cos \alpha - h^0 \sin \alpha], \quad (66)$$

$$H_u^2 = \frac{1}{\sqrt{2}} [v_u + H^0 \sin \alpha + h^0 \cos \alpha]. \quad (67)$$

The ρ couplings from the Stueckelberg extension are given by [7]

$$\mathcal{L}_{st} = m_\rho \rho \sum_i g_X Q_i \tilde{z}_i z_i \quad (68)$$

$$= m_\rho g_X \rho \left[Q_E \tilde{E}_L^* \tilde{E}_L + Q_{E^c} \tilde{E}_R^* \tilde{E}_R + Q_{E'} \tilde{E}_L'^* \tilde{E}_L' + Q_{E'^c} \tilde{E}_R'^* \tilde{E}_R' \right] , \quad (69)$$

where $Q_E = -Q_{E^c} = Q_{E'} = -Q_{E'^c}$. Next we write the above interactions in a mass diagonal basis using the following relations

$$(\tilde{E}_R^* \tilde{E}_L + \tilde{E}_L^* \tilde{E}_R) = \sin 2\xi (-\tilde{E}_1^* \tilde{E}_1 + \tilde{E}_2^* \tilde{E}_2) + \cos 2\xi (\tilde{E}_1^* \tilde{E}_2 + \tilde{E}_2^* \tilde{E}_1) , \quad (70)$$

$$(\tilde{E}_L^* \tilde{E}_L - \tilde{E}_R^* \tilde{E}_R) = \cos 2\xi (\tilde{E}_1^* \tilde{E}_1 - \tilde{E}_2^* \tilde{E}_2) + \sin 2\xi (\tilde{E}_1^* \tilde{E}_2 + \tilde{E}_2^* \tilde{E}_1) . \quad (71)$$

The relations above hold in the approximation when the off-diagonal terms in Eq. (7) are neglected. The relevant interactions in the mass diagonal basis are given by

$$\mathcal{L} = \mathcal{L}_{st} + \mathcal{L}_\gamma + \mathcal{L}_{EEh^0/H^0} , \quad (72)$$

$$\begin{aligned} \mathcal{L}_{st} &= m_\rho g_X Q_{E\rho} \left[\cos 2\xi (\tilde{E}_1^* \tilde{E}_1 - \tilde{E}_2^* \tilde{E}_2) + \sin 2\xi (\tilde{E}_1^* \tilde{E}_2 + \tilde{E}_2^* \tilde{E}_1) \right] \\ &+ m_\rho g_X Q_{E'\rho} \left[\cos 2\xi' (\tilde{E}_1'^* \tilde{E}_1' - \tilde{E}_2'^* \tilde{E}_2') + \sin 2\xi' (\tilde{E}_1'^* \tilde{E}_2' + \tilde{E}_2'^* \tilde{E}_1') \right] , \end{aligned} \quad (73)$$

$$\begin{aligned} \mathcal{L}_\gamma &= ieq_E (\tilde{E}_1^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}_1 + \tilde{E}_2^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}_2) A^\mu \\ &+ ieq_{E'} (\tilde{E}_1'^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}_1' + \tilde{E}_2'^* \overset{\leftrightarrow}{\partial}_\mu \tilde{E}_2') A^\mu , \end{aligned} \quad (74)$$

$$\begin{aligned} \mathcal{L}_{EEh^0/H^0} &= -\frac{g_2 m_E}{2M_W \cos \beta} \left[(A_E \cos \alpha + \mu \sin \alpha) H^0 + (-A_E \sin \alpha + \mu \cos \alpha) h^0 \right] \\ &\times \left[\sin 2\xi (-\tilde{E}_1^* \tilde{E}_1 + \tilde{E}_2^* \tilde{E}_2) + \cos 2\xi (\tilde{E}_1^* \tilde{E}_2 + \tilde{E}_2^* \tilde{E}_1) \right] \\ &- \frac{g_2 m_{E'}}{2M_W \sin \beta} \left[(A_{E'} \sin \alpha + \mu \cos \alpha) H^0 + (A_{E'} \cos \alpha - \mu \sin \alpha) h^0 \right] \\ &\times \left[\sin 2\xi' (-\tilde{E}_1'^* \tilde{E}_1' + \tilde{E}_2'^* \tilde{E}_2') + \cos 2\xi' (\tilde{E}_1'^* \tilde{E}_2' + \tilde{E}_2'^* \tilde{E}_1') \right] . \end{aligned} \quad (75)$$

These are the interactions that are used in the analysis of the paper.

B $h^0 h^0 \rightarrow \rho\rho$

The interaction between ρ and the Higgs boson can be parameterized as follows

$$\mathcal{L} = m_\rho \frac{g_{\rho hh}}{2!} \rho h^0 h^0 . \quad (76)$$

The averaged matrix element square for the process $(h^0 h^0 \rightarrow \rho\rho)$ is given by (exchanging a Higgs in both t- and u- channels)

$$|\overline{\mathcal{M}}|^2 = m_\rho^4 g_{\rho hh}^4 \left[\frac{1}{(p_3 - p_1)^2 - m_{h^0}^2} + \frac{1}{(p_4 - p_1)^2 - m_{h^0}^2} \right]^2 . \quad (77)$$

The annihilation rate is given by

$$v_{\text{rel}} \sigma = \frac{1}{2} \frac{\beta_f}{16\pi s} \int_{-1}^1 dz |\overline{\mathcal{M}}|^2 = m_\rho^4 \frac{2g_{\rho hh}^4}{\pi s^3} \frac{\beta_f}{(1 + \beta_f^2)^2} \left[\frac{a^2}{a^2 - 1} + \frac{a}{2} \ln \left(\frac{a+1}{a-1} \right) \right] . \quad (78)$$

Here $\beta_i \equiv \sqrt{1 - 4m_h^2/s}$, $\beta_f \equiv \sqrt{1 - 4m_\rho^2/s}$, $a \equiv (1 + \beta_f^2)/(2\beta_i\beta_f)$. This cross section is suppressed by $m_\rho^4/s^2 \simeq (m_\rho/2m_{h^0})^4 \sim 10^{-30}$. In the limit $\beta_i \rightarrow 0$ and $\beta_f \rightarrow 1$, we get

$$v_{\text{rel}}\sigma = m_\rho^4 \frac{g_{\rho hh}^4}{\pi s^3} \simeq 10^{-36} \text{ GeV}^{-2} . \quad (79)$$

For the annihilation process to make a significant contribution ($v_{\text{rel}}\sigma$) should be the range $10^{-23} - 10^{-24} \text{ GeV}^{-2}$. Thus the result of Eq. (79) is far too small.

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